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13. ABSTRACT *(Maximum 200 words)*

In the area of global optimization, we have analyzed the necessary and sufficient condition for the simulated annealing algorithm to hit the global minimum with probability. This entailed the development of a new theory of balance of recurrence orders for time-inhomogeneous Markov chains.

In the area of adaptive control and filtering, we have developed the first convergence theory for least-squares based adaptive control - the most popular scheme. We have also developed a theory of parallel model adaptation which resolves the question of convergence of the output error identification and adaptive IIR filtering algorithms, which has been an open probem for about a decade now. Also we have proposed new algorithms for adaptive feedforward control and adaptive active noise cancelling, and developed their analysis. We have applied for a patent on the latter scheme. In the area of robustness, we have shown that the simple modification of projecting the parameter estimates to stay in a compact convex set gives robustness not only with respect to bounded disturbances but also unmodeled dynamics. This resolves a question open for more than a decade.

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ADAPTIVE INFORMATION PROCESSING AND GLOBAL OPTIMIZATION

FINAL REPORT

P. R. KUMAR

NOVEMBER 29, 1991

U. S. ARMY RESEARCH OFFICE

CONTRACT NUMBER DAAL 03-88-K0046

UNIVERSITY OF ILLINOIS

Final Report on Contract No. DAAL-03-88-K0046

P. R. Kumar

1. FOREWORD

In this contract, we have conducted research on, and obtained several important results in the areas of adaptive control, filtering and signal processing and global optimizaton.

4A. STATEMENT OF THE PROBLEM STUDIED

We have examined three major problem areas. First, we have analyzed the simulated annealing algorithm for global optimization. Second, we have studied the asymptotic performance of several algorithms for adaptive control filtering and signal processing. Third, we have studied how to obtain robustness of adaptation algorithms to ever present unmodeled dynamics and disturbances.

4B. SUMMARY OF THE MOST IMPORTANT RESULTS

Simulated annealing with temperature cooling gives rise to a Markov chain with time-inhomogeneous transition probablities. We developed a new concept of "orders of recurrence," and created a new theory of "balance of recurrence orders" to analyze such Markov chains. This notion of balance is completely different from usual balance, which equates flux in and out of every spatial region in equilibrium. Our balance theory is across time, not space, and is the first such for time-varying processes. As a consequence of this theory, we have determined the necessary and sufficient condition on the cooling rate in order for simulated annealing to hit the global minimum with probability one; see [1].

In the area of adaptive control, we have developed the first convergence analysis of any stochastic adaptive controller using a recursive least squares parameter estimator in Gaussian noise, an open question since 1973. It should be noted that recursive least squares is by far the more popular choice in comparison with gradient based schemes; see [2]. We have also developed a performance analysis for pole-zero placement schemes, and generalized certainty equivalent controllers.

We have developed a comprehensive theory of adaptation for parallel model schemes. This includes the establishment of stability and optimality of output error identification and adaptive IIR filtering algorithms, an open question for more than a decade. We have proposed new algorithms for adaptive feedforward control, a major practical application area, and adaptive active noise cancelling;

see [3]. For the latter scheme, the university has applied for a patent. We believe the problem of noise control is a major growth area in the coming decades.

In the area of robustness enhancement and analysis, we have shown that by simply projecting the parameter estimates onto a compact convex set, we can obtain robustness of adaptive algorithms with respect to both bounded disturbances as well as small unmodeled dynamics; see [4]. Such effects are always present in any practical application, and this has been a major area of adaptive systems research for the past nine years. Our work proving that such a simple modification gives robustness, shows that the several modifications proposed by researchers over the past nine years are unnecessary.

4C. List of All Publications and Technical Reports

Books

1. Wei Ren and P. R. Kumar, "The Convergence of Output Error Recursions in Infinite Order Moving Average Noise," to appear in the Proceedings of the IMA Summer Program on *New Directions in Time Series Analysis*, Institute for Mathematics and its Applications, Minneapolis, MN, October July 1-29, 1990.

2. Wei Ren and P. R. Kumar, "Stochastic Adaptive System Theory: Recent Advances and a Reappraisal," *Foundations of Adaptive Control*, Lecture Notes in Control and Information Sciences, vol. 160, pp. 269–307, P. V. Kokotovic, Editor, Springer-Verlag, New York, 1991.

3. Sanjeev M. Naik, P. R. Kumar and B. Erik Ydstie, "Robust Continuous-Time Adaptive Control by Parameter Projection," *Foundations of Adaptive Control*, vol. 160, Lecture Notes in Control and Information Sciences, P. V. Kokotovic (Ed), Springer-Verlag, New York, 1991.

4. Steve Lu and P. R. Kumar, "On Dynamic Scheduling of Manufacturing Systems," *Communication, Control and Signal Processing: Proceedings of the 1990 Bilkent International Conference on New Trends in Communication, Control and Signal Processing*, vol. II, pp. 1643–1649, E. Arikan, Editor, Elsevier, Amsterdam, 1990.

Articles in Journals or Conference Proceedings

1. D. P. Connors and P. R. Kumar, "Balance of Recurrence Order in Time-Inhomogeneous Markov Chains With Application to Simulated Annealing," *Probability in the Engineering and Informational Sciences*, vol. 2, pp. 157–184, 1988.

2. L. Praly, S-F. Lin and P. R. Kumar, "A Robust Adaptive Minimum Variance Controller, *SIAM Journal on Control and Optimization*, vol. 27, no. 2, pp. 235–266, March 1989.

3. J. Perkins and P. R. Kumar, "Stable Distributed Real-Time Scheduling of Flexible Manufacturing/Assembly/Disassembly Systems," *IEEE Transactions on Automatic Control*, vol. 34, no. 2, pp. 139–148, February 1989.

4. "Convergence Analysis of Self-Tuning Controllers by Bayesian Embedding," *International Symposium on the Mathematical Theory of Networks and Systems*, Amsterdam, June 19-23, 1989.

5. D. P. Connors and P. R. Kumar, "Simulated Annealing Type Markov Chains and their Order Balance Equations," *SIAM Journal on Control and Optimization*, vol. 27, no. 6, pp. 1440–1462, November 1989.

6. S-F. Lin and P. R. Kumar, "Parameter Convergence in the Stochastic Gradient Adaptive Control Law," *Proceedings of the Twenty-Seventh Conference on Decision and Control*, pp. 1211–1212, Austin, Texas, Dec. 7-9, 1988. (Invited Paper).

7. P. R. Kumar, "Simulated Annealing and Balance of Recurrence Orders," *Proceedings of the SPIE Symposium: High Speed Computing II*, pp. 103–106, vol. 1058, Keith Bromley, Editor, Los Angeles, January 17-18, 1989.

8. P. R. Kumar, "Convergence of Adaptive Control Schemes Using Least-Squares Parameter Estimates," *IEEE Transactions on Automatic Control*, vol. 35, no. 5, pp. 416–424, April 1990.

9. H-F. Chen, P. R. Kumar and J. H. van Schuppen, "On Kalman Filtering for Conditionally Gaussian Systems With Random Matrices," *Systems and Control Letters*, vol. 13, no. 5, pp. 397–404, December 1989.

10. P. R. Kumar, "Convergence of Least-Squares Parameter Estimate Based Adaptive Control Schemes, *Proceedings of the 11th IFAC World Congress*, vol. 4, pp. 87–91, August 13-17, 1990, Tallinn, U.S.S.R.

11. Wei Ren and P. R. Kumar, "Adaptive Active Noise Control: Structures, Algorithms and Convergence Analysis," *Proceedings of Internoise 89*, pp. 435–440, Newport Beach, CA, Dec. 4-6, 1989.

12. Steve H. Lu and P. R. Kumar, "Distributed Scheduling Based on Due Dates and Buffer Priorities," *IEEE Transactions on Automatic Control*, pp. 1406–1416, December 1991.

13. Wei Ren and P. R. Kumar, "The Convergence of Output Error Identification and Adaptive IIR Filtering Algorithms in the Presence of Colored Noise," *Proceedings of the 29th IEEE Conference on Decision and Control.* pp. 3534–3539, Honolulu, Hawaii, December 1990.

14. C. H. Lu and P. R. Kumar, "Distributed Scheduling Based on Due Dates and Buffer Prioritization." *Proceedings of the 29th IEEE Conference on Decision and Control.* pp. 565–567, Honolulu, Hawaii, December 1990.

15. Sanjeev M. Naik and P. R. Kumar, "A Robust Adaptive Controller for Continuous Time Systems," *Proceedings of the 1991 American Control Conference.* vol. 1, pp. 132–137, June 1991.

16. Wei Ren and P. R. Kumar, "Interlacing is not Necessary for Adaptive Control," *Proceedings of the 1991 American Control Conference*, vol. 1, pp. 661–666, June 1991.

17. Sanjeev M. Naik, P. R. Kumar and B. Erik Ydstie, "Robust Continuous Time Adaptive Control by Parameter Projection," to appear in *IEEE Transactions on Automatic Control*, February 1992, and the *30th IEEE Conference on Decision and Control.* November 29, 1990.

18. Wei Ren and P. R. Kumar, "Recent Results on Least Squares Based Adaptive Control of Linear Stochastic Systems in White Noise," *Sadhana*, pp. 397–404, vol. 15, nos. 4 & 5, December 1990.

19. Wei Ren and P. R. Kumar, "The Convergence of Stochastic Adaptive Controllers," *Proceedings of the Twenty-fifth Annual Conference on Information Sciences and Systems*, pp. 931–933, Johns Hopkins University, 1991.

20. Kevin Buescher and P. R. Kumar, "Learning and Estimating Classes of Sets over Classes of Probabilities," *Proceedings of the Twenty-fifth Annual Conference on Information Sciences and Systems*, pp. 108–113, Johns Hopkins University, 1991.

21. Sanjeev M. Naik and P. R. Kumar, "Robust Adaptive Control of Continuous Time Systems by Parameter Projection," *Proceedings of the Twenty-fifth Annual Conference on Information Sciences and Systems*, p. 934, Johns Hopkins University, 1991.

22. Wei Ren and P. R. Kumar, "Stochastic Parallel Model Adaptation: Theory and Applications to Active Noise Cancellation, Feedforward Control, IIR Filtering and Identification," to appear in *IEEE Transactions on Automatic Control*, and the *Proceedings of the 30th IEEE Conference on Decision and Control.*

23. Sanjeev M. Naik and P. R. Kumar, "Robustness of Extended Least Squares Based Adaptive Control," to appear in *Proceedings of the 30th IEEE Conference on Decision and Control.*

24. Wei Ren, "Stochastic Adaptive System Theory for Identification, Filtering, Prediction and Control," Ph. D. Thesis, August 1991. University of Illinois, Urbana-Champaign.

25. Rayadurgam Ravikanth, "Simulation of Discrete-Time Systems Using ISIM," M. .S. Thesis, 1991

4D. LIST OF ALL PARTICIPATING SCIENTIFIC PERSONNEL SHOWING ANY ADVANCED DEGREES EARNED BY THEM WHILE EMPLOYED ON THE PROJECT

i) Professor P. R. Kumar

ii) Wei Ren, Ph.D.

iii) Rayadurgam Ravikanth, M.S.

iv) Sanjeev M. Naik

5. REPORT OF INVENTIONS

Wei Ren and P. R. Kumar, "Adaptive Noise Cancellation System," Patent applied for by the University of Illinois.

Wei Ren and G. W. Swenson, Jr., "Active Acoustic Surfaces with Adjustable Reflection/Absorption Properties for Multi-Purpose Sound Effects," Patent applied for by the University of Illinois.

6. BIBLIOGRAPHY

1. D. P. Connors and P. R. Kumar, "Balance of Recurrence Order in Time-Inhomogeneous Markov Chains With Application to Simulated Annealing," *Probability in the Engineering and Informational Sciences*, vol. 2, pp. 157–184, 1988.

2. P. R. Kumar, "Convergence of Adaptive Control Schemes Using Least-Squares Parameter Estimates," *IEEE Transactions on Automatic Control*, vol. 35, no. 5, pp. 416–424, April 1990.

3. Wei Ren and P. R. Kumar, "Stochastic Parallel Model Adaptation: Theory and Applications to Active Noise Cancellation, Feedforward Control, IIR Filtering and Identification," to appear in *IEEE Transactions on Automatic Control*, 1992.

4. Sanjeev M. Naik, P. R. Kumar and B. Erik Ydstie, "Robust Continuous Time Adaptive Control by Parameter Projection," to appear in *IEEE Transactions on Automatic Control*, February 1992.